

# Minimal Length Scale in Annihilation

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## Abstract

Experimental data suggest the existence of a minimal length scale in annihilation process for the reaction  $e^+e^- \rightarrow \gamma\gamma(\gamma)$ . Nonlinear electrodynamics coupled to gravity and satisfying the weak energy condition predicts, for an arbitrary gauge invariant lagrangian, the existence of a spinning charged electromagnetic soliton asymptotically Kerr-Newman for a distant observer with a gyromagnetic ratio  $g = 2$ . Its internal structure includes an equatorial disk of de Sitter vacuum which has properties of a perfect conductor and ideal diamagnetic, and displays superconducting behavior within a single spinning soliton. De Sitter vacuum supplies a particle with the finite positive electromagnetic mass related to breaking of space-time symmetry. We apply this approach to interpret the existence of a minimal characteristic length scale in annihilation.

## 1 Introduction

The question of intrinsic structure of a fundamental charged spinning particle such as an electron, has been discussing in the literature since its discovery by Thomson in 1897. One can roughly distinguish two approaches. First one deals with point-like models. In quantum field theory a particle is assumed point-like, and classical models of the first type consider point-like particles described by various generalizations of the classical Hamilton lagrangian  $(-mc\sqrt{\dot{x}\dot{x}})$  involving higher derivatives terms or inner variables [1], and making use of geometry [2] or symmetry [3] constraints. An elegant recent example is the Staruszkiewicz relativistic rotator as a fundamental dynamical system whose Casimir invariants are parameters, but not constants of motion [4]. This gives rise to a classical model for a point-like relativistic spinning particle which can be extended to the case when it interacts with an external electromagnetic field [5].

Another type of point-like models of spinning particles goes back to the Schrödinger suggestion that the electron spin can be related to its Zitterbewegung motion [6]. The concept of Zitterbewegung - trembling motion due to the rapid oscillation of a spinning particle around

its classical worldline, has been worked out in a lot of papers [7, 8, 9] motivated by attempts to understand the intrinsic structure of the electron [10]. For example, in models based on the Clifford algebras, the electron is associated with the mean motion of its point-like constituent whose trajectory is a cylindrical helix ([8] and references therein).

Second type approach deals with *extended* particle models.

The concept of an extended electron, proposed by Abraham [11] and Lorentz [12], that makes finite the total field energy, assumed the electron to be a spherical rigid object. While point-like models typically suffer from an infinite self-energy, the main problem encountered by extended models, was to prevent an electron from flying apart under the Coulomb repulsion. Theories based on geometrical assumptions about the "shape" or distribution of a charge density, were compelled to introduce *cohesive* forces of non-electromagnetic origin (the Poincaré stress) testifying that replacing a point charge with an extended one is impossible within electrodynamics since it demands introducing cohesive non-electromagnetic forces.

It was clearly formulated by Dirac who proposed in 1962 the model of an electron as a charged conducting surface; outside the surface, the Maxwell equations hold; inside there is no field; a non-Maxwellian force was assumed as kind of a surface tension, so the electron is pictured as a spherical bubble in the electromagnetic field [13].

Similar picture was obtained in the frame of the Dirac non-linear electrodynamics in the Minkowski space, based on imposing a nonlinear gauge on a vector potential [14]. The field equations of this theory have soliton-like solutions which can be regarded as describing a charged particle [15], and admit further generalization [16] to yield a classical model for a spherical charged spinning particle looking as a hole in an electromagnetic field and demonstrating a solitonic behavior: the interior of a particle is accessible to any other particle (apart from electromagnetic repulsion) [16].

The Kerr-Newman geometry discovered in linear electrodynamics coupled to gravity [17]

$$ds^2 = -dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \frac{(2mr - e^2)}{\Sigma} (dt - a \sin^2 \theta d\phi)^2 + (r^2 + a^2) \sin^2 \theta d\phi^2; \quad A_i = -\frac{er}{\Sigma} [1; 0, 0, -a \sin^2 \theta] \quad (1)$$

where  $A_i$  is associated electromagnetic potential, and

$$\Sigma = r^2 + a^2 \cos^2 \theta; \quad \Delta = r^2 - 2mr + a^2 + e^2, \quad (2)$$

have inspired further search for an electromagnetic image of the electron since Carter [18] found that the parameter  $a$  couples with the mass  $m$  to give the angular momentum  $J = ma$ , and with the charge  $e$  to give an asymptotic magnetic momentum  $\mu = ea$ , so that there is no freedom in variation of the gyromagnetic ratio  $e/m$  which is exactly the same as predicted by the Dirac

equation,  $g = 2$ , and it is possible to choose the parameters in such a way that they agree with the electron parameters; in the units  $\hbar = c = G = 1$  we have  $a = 1/2m$ , and the length scale determined by  $a$  is about the Compton wavelength [18].

This result suggested that the spinning electron might be classically visualized as a massive charged source of the Kerr-Newman field [19, 20].

The point is that the Kerr-Newman geometry itself cannot model a particle for the very serious reason discovered by Carter [18]: In the case  $a^2 + e^2 > m^2$  appropriate for modelling a particle since there are no Killing horizons and the manifold is geodesically complete, just in this case the whole space is a single vicious set, i.e. such a set in which any point can be connected to any other point by both a future and a past directed timelike curve, which means complete and unavoidable breakdown of causality [18].

The Kerr-Newman solution belongs to the Kerr family of the source-free Maxwell-Einstein equations, the only contribution to a stress-energy tensor comes from a source-free electromagnetic field [18]. It can represent the exterior fields of spinning charged bodies. The question of an interior material source for these exterior fields, is the most intriguing question addressed in a lot of papers. The source models for the Kerr-Newman interior can be roughly divided into disk-like[19, 21, 22], shell-like[23, 24, 20], bag-like[25, 26, 27, 28, 29, 30], and string-like ([31] and references therein). Characteristic radius of a disk is the Compton wavelength  $\lambda_e \simeq 3.9 \times 10^{-11} cm$ , and in bag-like models thickness of an ellipsoid is of order of the electron classical radius,  $r_e \simeq 2.8 \times 10^{-13} cm$ .

The problem of matching the Kerr-Newman exterior to a rotating material source does not have a unique solution, since one is free to choose arbitrarily the boundary between the exterior and the interior [19].

On the other hand, in nonlinear electrodynamics coupled to gravity (NED-GR), the field equations admit regular solutions asymptotically Kerr-Newman for a distant observer, which describe a spinning electromagnetic soliton (i.e., a regular finite-energy solution of the nonlinear field equations, localized in the confined region and holding itself together by its own self-interaction) [32]. Its generic features valid for an arbitrary nonlinear lagrangian  $\mathcal{L}(F)$  can be outlined briefly as follows. In NED-GR solutions satisfying the weak energy condition (non-negative density as measured along any time-like curve), a spherically symmetric electrically charged soliton has obligatory de Sitter center in which the electric field vanishes while the energy density of electromagnetic vacuum achieves its maximal finite value representing self-interaction [33]. De Sitter vacuum supplies a particle with the finite positive electromagnetic mass related to breaking of space-time symmetry from the de Sitter group in the origin [33, 34]. By the Gürses-Gürsey algorithm based on the Newman-Trautman technique [35] it transforms into a spinning electromagnetic soliton with the Kerr-Newman behavior for a distant observer.

Its internal structure includes the equatorial disk of a rotating de Sitter vacuum which has properties of a perfect conductor and ideal diamagnetic, and displays superconducting behavior within a single spinning particle [32].

Experimental limits on size of a lepton [36] are much less than its Compton wavelength and classical radius. This suggests that an extended fundamental particle can have one more, relatively small characteristic length scale, related to gravity.

To get an evidence for an extended particle picture, we worked out data of experiments performed to search for compositeness or to investigate a non-point-like behavior, with focus on characteristic energy scale related to characteristic length scale of interaction region [37].

In this paper we outline the experimental results on the QED reaction measuring the differential cross sections for the process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  at energies from  $\sqrt{s}=55$  GeV to 207 GeV using the data collected with the VENUS, TOPAZ, ALEPH, DELPHI L3 and OPAL from 1989 to 2003. Experimental data suggest the existence of a minimal length scale in annihilation reaction  $e^+e^- \rightarrow \gamma\gamma(\gamma)$ . The global fit to the data is 5 standard deviations from the standard model expectation for the hypotheses of an excited electron and of contact interaction with non-standard coupling [38], corresponding to the cut-off scale  $E_\Lambda = 1.253$  TeV and to related characteristic length scale  $l_e \simeq 1.57 \times 10^{-17}$  cm. We interpret this experimental effect by applying theoretical results obtained in nonlinear electrodynamics coupled to gravity.

## 2 Experimental evidence for an extended lepton

The purely electromagnetic interaction  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  is ideal to test QED because it is not interfered by the  $Z^0$  decay. This reaction proceeds via the exchange of a virtual electron in the t - and u - channels, while the s - channel is forbidden due to angular momentum conservation. Differential cross sections for the process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$ , are measured at energies from  $\sqrt{s}=55$  GeV to 207 GeV using the data collected with the VENUS [39], TOPAZ [40], ALEPH [41], DELPHI [42], L3 [43] and OPAL [44] detector from 1989 to 2003.

Comparison of the data with the QED predictions are used to constrain models with an excited electron of mass  $m_{e^*}$  replacing the virtual electron in the QED process [45], and a model with deviation from QED arising from an effective interaction with non-standard  $e^+e^-\gamma$  couplings and  $e^+e^-\gamma\gamma$  contact terms [46].

A heavy excited electron could couple to an electron and a photon via magnetic interaction with an effective lagrangian [47]

$$\mathcal{L}_{excited} = \frac{e\lambda}{2m_{e^*}} \overline{\psi_{e^*}} \sigma_{\mu\nu} \psi_e F^{\mu\nu} \quad (3)$$

Here  $\lambda$  is the coupling constant,  $F^{\mu\nu}$  the electromagnetic field,  $\psi_{e^*}$  and  $\psi_e$  are the wave function

of the heavy electron and the electron respectively;  $\lambda$  and  $m_{e^*}$  are the model parameters. Differential cross-section involves a deviation term  $\delta_{new}$  from the QED differential cross-section including radiative effects up to  $O(\alpha^3)$ . The modified equation reads

$$(d\sigma/d\Omega)_{theo} = (d\sigma/d\Omega)_{O(\alpha^3)}(1 + \delta_{new}) \quad (4)$$

If the center-of-mass energy  $\sqrt{s}$  satisfies the condition  $s/m_{e^*}^2 \ll 1$ , then  $\delta_{new}$  can be approximated as

$$\delta_{new} = s^2/2(1/\Lambda^4)(1 - \cos^2 \Theta) \quad (5)$$

In this approximation, the parameter  $\Lambda$  is the QED cut-off parameter,  $\Lambda^2 = m_{e^*}^2/\lambda$ . In the case of arbitrary  $\sqrt{s}$  the full equation of ref.[47] is used to calculate  $\delta_{new} = f(m_{e^*})$ . The angle  $\Theta$  is the open angle of the two most energetic photons emitted with angles  $\Theta_1$  and  $\Theta_2$  with respect to the beam axis defined below

$$|\cos(\Theta)| = 1/2(|\cos(\Theta_1)| + |\cos(2\pi - \Theta_2)|) \quad (6)$$

The third order QED differential cross section is calculated numerically up to  $O(\alpha^3)$ , by generating a high number of Monte Carlo  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  events [48, 49]. The angular distribution of these events was fitted with a high order polynomial function to get an analytical equation for the cross section as function of the scattering angle defined in (6).

An overall  $\chi^2$  test between 55 GeV and 207 GeV was performed on the published differential cross sections. The single results of the different  $1/\Lambda^4[1/\text{GeV}^4]$  minima are displayed in Fig.1. The upper part shows the 4 LEP experiments and the lower part shows the combined in three groups results from TRISTAN, LEP 1, LEP 2, and the overall result of  $1/\Lambda^4 = -(1.11 \pm 0.70) \times 10^{-10} \text{GeV}^{-4}$ .

Systematic errors arise from the luminosity evaluation, from the selection efficiency, background evaluations, the choice to use the Born level or  $\alpha^3$  theoretical QED cross section as reference cross section, the choice of the fit procedure, the choice of the fit parameter and the choice of the scattering angle  $|\cos\Theta|$  in particular in comparison between data and theoretical calculation.

The maximum estimated error for the value of the fit from the luminosity, selection efficiency and background evaluations is approximately  $\delta\Lambda/\Lambda = 0.01$  [50]. The choice of the theoretical QED cross section was studied with 1882  $[e^+e^- \rightarrow \gamma\gamma(\gamma)]$  events from the L3 detector [50]. In Fig. 2 the measured data points of the  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  reaction are shown together with the QED Born and the  $\alpha^3$  level approximations. In part b) the sensitivity of the measured data points to QED cross sections is visible.

A drop in the  $\chi^2$  by approximately a factor two favors the QED  $\alpha^3$  level to be used for the fit. For a small sample of  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  events the fit values  $\Lambda$  are compared for  $\chi^2$ , Maximum-Likelihood, Smirnov-Cramer von Mises, Kolmogorov test, all with and without binning [51].

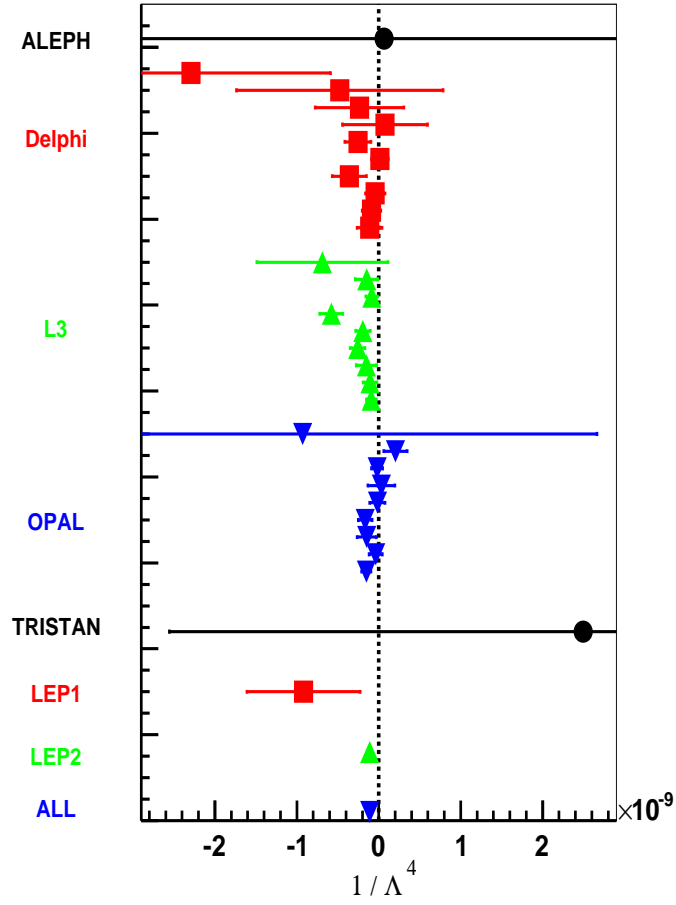


Figure 1: The  $\chi^2$  minima for all  $1/\Lambda^4[\text{GeV}^{-4}]$  values.

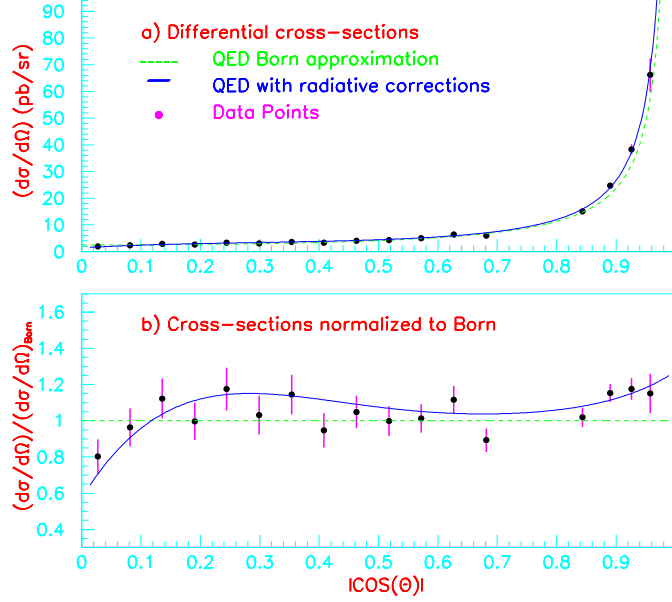


Figure 2: QED cross section and experimental data

An approximately  $\delta\Lambda/\Lambda = 0.005$  effect is estimated for the overall fit with the fit parameter  $P = (1/\Lambda^4)$ . The  $\chi^2$  overall fit displays a minimum in the  $\chi^2$  as we see in Fig.3).

The use of different definitions of scattering angles [40] introduces in the  $|\cos(\Theta)|$  an error of approximately  $\delta |\cos(\Theta)| = 0.0005$ . In the worst case of scattering angles close to  $90^\circ$ , the  $|\cos(\Theta)|_{\text{experiment}} \sim 0.05$  would result in  $(\delta\Lambda/\Lambda)_{\delta|\cos(\Theta)|} = 0.01$ . The total systematic error is  $\delta\Lambda/\Lambda \approx 0.015$ .

The hypothesis used in (3) and (4) assumes that an excited electron will increase the total QED- $\alpha^3$  cross section and change the angular distribution of the QED cross section. Contrary to these expectations, the fit expresses a minimum with a negative fit parameter  $1/\Lambda^4$  of a significance of approximately  $5 \times \sigma$ .

For an effective contact interaction with non-standard coupling, a cut-off parameter  $\Lambda_C$  is introduced to describe the scale of interaction with the lagrangian [46]

$$\mathcal{L}_{\text{contact}} = i\bar{\psi}_e \gamma_\mu (D_\nu \psi_e) \left( \frac{\sqrt{4\pi}}{\Lambda_{C6}^2} F^{\mu\nu} + \frac{\sqrt{4\pi}}{\tilde{\Lambda}_{C6}^2} \tilde{F}^{\mu\nu} \right) \quad (7)$$

The effective Lagrangian chosen in this case has an operator of dimension 6, the wave function of the electrons is  $\psi_e$ , the QED covariant derivative is  $D_\nu$ , the tilde on  $\tilde{\Lambda}_{C6}$  and  $\tilde{F}^{\mu\nu}$

stands for duals. As in the case of excited electron the corresponding differential cross section involves a deviation term  $\delta_{new}$  from the QED differential cross section including radiative effects up to  $O(\alpha^3)$ , and  $\delta_{new}$  reads as

$$\delta_{new} = s^2/(2\alpha)(1/\Lambda_{C6}^4 + 1/\tilde{\Lambda}_{C6}^4)(1 - \cos^2 \Theta) \quad (8)$$

The angle  $\Theta$  is the angle of the emitted photons with respect to the beam axis defined in (6). For the fit procedures discussed below we set  $\Lambda_{C6} = \tilde{\Lambda}_{C6} = \Lambda_C$ .

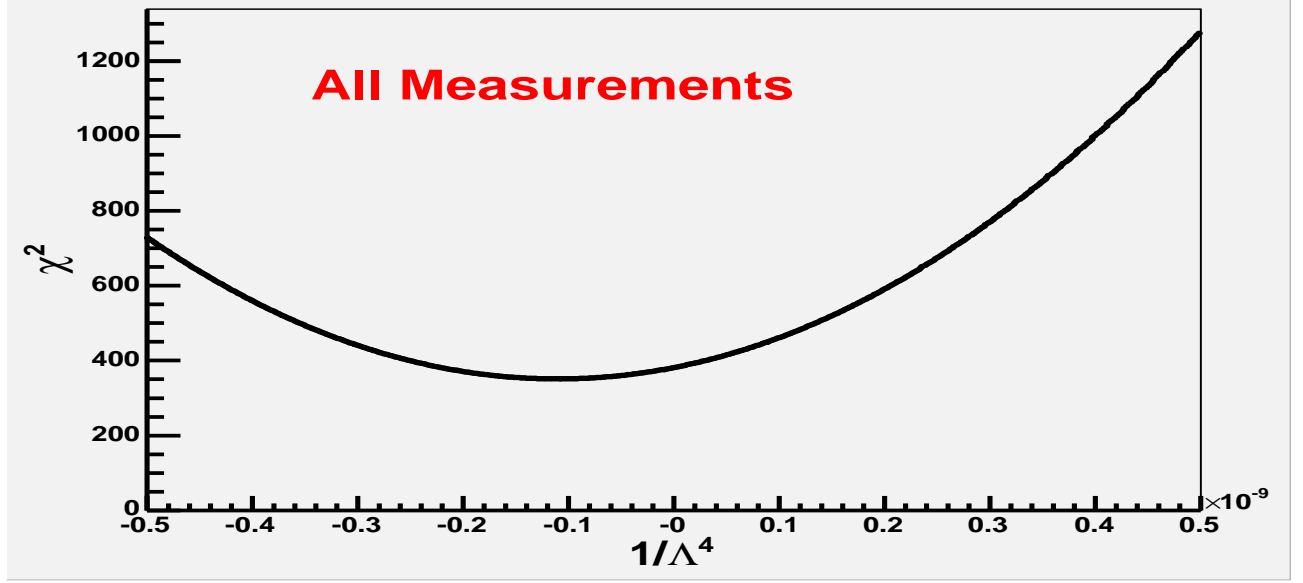


Figure 3: A minimum in the  $\chi^2$  for the overall fit ( $1/\Lambda^4[\text{GeV}^{-4}]$ ).

The  $\chi^2$  fit for the hypothesis of the excited electron, eq.(3), was repeated for the hypothesis of the effective contact interaction, eq.(7), using  $(1/\Lambda_C^4)$  as fit parameter. As in the hypothesis of the excited electron also for the effective contact interaction, an increase of the total QED- $\alpha^3$  cross section and a change of the angular distribution were expected. In contrary to both hypothesis also the best fit value of all data  $(1/\Lambda_C^4)_{best} = -(4.05 \pm 0.73) \times 10^{-13} \text{GeV}^{-4}$  is negative with significance about  $5 \times \sigma$ . The fit does not allow to distinguish between both above hypothesis. The results indicate decreasing cross section of the process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  with respect to that predicted by pure QED. The calculation of the QED- $\alpha^3$  cross section assumes a scattering center as a point. If the electron is an extended object, its structure would modify the QED cross section if the test distances (CM-scattering energy) are smaller than its characteristic size.

It is remarkable that for both hypothesis the excited electron and effective contact interaction, the  $\chi^2$  test leads to a best fit value  $(1/\Lambda^4)_{best}$  and  $(1/\Lambda_C^4)_{best}$  for the complete data set with a  $5\sigma$  significance.



With the best value  $(1/\Lambda)_C^4$  one can calculate the energy scale  $E_\Lambda = (\Lambda_C)_{best} = 1.253$  TeV [38] which corresponds to a length scale  $l_e \simeq 1.57 \times 10^{-17}$  cm as the distance of the closest approach of particles which cannot be made smaller and suggests the existence of a minimal characteristic length scale in annihilation.

### 3 Electromagnetic soliton

In the nonlinear electrodynamics minimally coupled to gravity (NED-GR), the action is given by (in geometrical units  $G = c = 1$ )

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} (\mathcal{R} - \mathcal{L}(F)); \quad F = F_{\mu\nu} F^{\mu\nu} \quad (9)$$

where  $\mathcal{R}$  is the scalar curvature. The gauge-invariant electromagnetic Lagrangian  $\mathcal{L}(F)$  is an arbitrary function of  $F$  which should have the Maxwell limit,  $\mathcal{L} \rightarrow F$ , in the weak field regime.

In the case of electrically charged structure, a field invariant  $F$  must vanish for  $r \rightarrow 0$  to guarantee regularity [53], and the electric field strength is zero in the center of any regular charged NED-GR structure. The field invariant  $F$  vanishes at both zero and infinity where it follows the Maxwell weak field limit. In both limits  $F \rightarrow -0$ , so that  $F$  must have at least one minimum in between, where an electrical field strength has an extremum too [53, 33].

A stress-energy tensor of a spherically symmetric electromagnetic field  $\kappa T_\nu^\mu = -2\mathcal{L}_F F_{\nu\alpha} F^{\mu\alpha} + \frac{1}{2}\delta_\nu^\mu \mathcal{L}$ , where  $\kappa = 8\pi G$ , has the algebraic structure

$$T_t^t = T_r^r \quad (10)$$

Symmetry of a source term leads to the metric [54]

$$ds^2 = g(r)dt^2 - \frac{dr^2}{g(r)} - r^2 d\Omega^2 \quad (11)$$

The metric function and mass function are given by

$$g(r) = 1 - \frac{2\mathcal{M}(r)}{r} : \quad \mathcal{M}(r) = \frac{1}{2} \int_0^r \rho(x) x^2 dx \quad (12)$$

For the class of regular spherical symmetric geometries with the symmetry of a source term given by (10), the weak energy condition leads inevitably to de Sitter asymptotic at approaching a regular center [54, 55]

$$p = -\rho; \quad g(r) = 1 - \frac{\Lambda}{3} r^2 \quad (13)$$

with cosmological constant  $\Lambda = 8\pi\rho_0$  where  $\rho_0 = \rho(r=0)$  is the finite density in the regular center. As a result, the mass of an object described by (10)-(12),  $m = \mathcal{M}(r \rightarrow \infty)$ , is generically

related to breaking of space-time symmetry from the de Sitter group in the origin, and to de Sitter vacuum trapped inside [55].

Regular electrically charged spherically symmetric solutions describe an electromagnetic soliton with the obligatory de Sitter center in which field tension goes to zero, while the energy density of the electromagnetic vacuum  $T_t^t$  achieves its maximal finite value which represents the de Sitter cutoff for the self-interaction divergent for a point charge [33].

For a distant observer, it is described by the Reissner-Nordström asymptotic

$$g(r) = 1 - \frac{r_g}{r} + \frac{e^2}{r^2} \quad (14)$$

where  $r_g = 2m$  is the Schwarzschild gravitational radius.

For all solutions specified by (10), there exists the surface of zero gravity at which the strong energy condition ( $\rho + \sum p_k \geq 0$ ) is violated which means that gravitational acceleration changes its sign and becomes repulsive [56, 54].

Spherically symmetric solutions satisfying the condition (10) belong to the Kerr-Schild class [30, 57]. By the Gürses-Gürsey algorithm [35] they can be transformed into regular solutions describing a spinning charged soliton. In the Boyer-Lindquist coordinates the metric is

$$ds^2 = \frac{2f - \Sigma}{\Sigma} dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 - \frac{4af \sin^2 \theta}{\Sigma} dt d\phi + \left( r^2 + a^2 + \frac{2fa^2 \sin^2 \theta}{\Sigma} \right) \sin^2 \theta d\phi^2 \quad (15)$$

$$\Sigma = r^2 + a^2 \cos^2 \theta; \quad \Delta = r^2 + a^2 - 2f(r) \quad (16)$$

The function  $f(r)$  in (15) is given by

$$f(r) = r\mathcal{M}(r) \quad (17)$$

where density profile in (12) is that for a nonlinear spherically symmetric electromagnetic field.

For NED-GR solutions satisfying the weak energy condition,  $\mathcal{M}(r)$  is everywhere positive function growing monotonically from  $\mathcal{M}(r) = 4\pi\rho_0 r^3/3$  as  $r \rightarrow 0$  to  $m$  as  $r \rightarrow \infty$ . The mass  $m$ , appearing in a spinning solution, is the finite positive electromagnetic mass [32, 33].

The condition of the causality violation [18] takes the form [32]

$$r^2 + a^2 + \Sigma^{-1} 2f(r) a^2 \sin^2 \theta < 0 \quad (18)$$

and is never satisfied due to non-negativity of the function  $f(r)$ .

In the geometry with the line element (15), the surfaces  $r = \text{const}$  are the oblate ellipsoids

$$r^4 - (x^2 + y^2 + z^2 - a^2)r^2 - a^2 z^2 = 0 \quad (19)$$

which degenerate, for  $r = 0$ , to the equatorial disk

$$x^2 + y^2 \leq a^2, \quad z = 0 \quad (20)$$

centered on the symmetry axis.

For a distant observer, a spinning electromagnetic soliton is asymptotically Kerr-Newman, with  $f(r) = mr - e^2/2$ , and the gyromagnetic ratio  $g = 2$ .

For  $r \rightarrow 0$  the function  $f(r)$  in (15) approaches de Sitter asymptotic

$$2f(r) = \frac{r^4}{r_0^2}; \quad r_0^2 = \frac{3}{\kappa\rho_0} \quad (21)$$

and the metric describes rotating de Sitter vacuum in the co-rotating frame [32].

In the NED-GR regular solutions, an internal equatorial disk (20) is filled with rotating de Sitter vacuum, it has properties of both perfect conductor and ideal diamagnetic, and displays superconducting behavior within a single spinning soliton [32].

## 4 Origin of a minimal length scale in annihilation

The minimum in the fit found with  $5 \times \sigma$  significance, corresponds to the characteristic length scale  $l_e \simeq 1.57 \times 10^{-17}$  cm related to the energy scale  $E_\Lambda \simeq 1.253$  TeV.

The existence of the limiting length scale  $l_e$  in experiments on annihilation, testifies for an extended particle rather than a point-like one. The effective size of an interaction region  $l_e$  corresponds to a minimum in  $\chi^2$ , so that it can be understood as a minimal length scale in annihilation which cannot be made smaller.

Generic features of electromagnetic soliton give some idea about the origin of the characteristic length scale  $l_e$  given by experiments. The certain feature of annihilation process is that at a certain stage a region of interaction is neutral and spinless. We can roughly model it by a spherical lump with de Sitter vacuum interior. The key point is the existence of zero-gravity surface at which strong energy condition is violated [56, 54] and gravitational acceleration becomes repulsive. The related length scale  $r_* \simeq (r_0^2 r_g)^{1/3}$  appears naturally in direct matching de Sitter interior to the Schwarzschild exterior [58].

The gravitational radius of a lump on the characteristic energy scale  $E_\Lambda \simeq 1.25$  TeV, is  $r_g \simeq 3.32 \times 10^{-49}$  cm. Adopting for the interior de Sitter vacuum the experimental vacuum expectation value for the electroweak scale  $E_{EW} = 246$  GeV related to the electron mass [59] we get the de Sitter horizon radius  $r_0 = 1.374$  cm. Characteristic radius of zero gravity surface is  $r_* \simeq 0.86 \times 10^{-16}$  cm, so that the scale  $l_e$  fits inside a region where gravity is already repulsive. The scale  $l_e$  can be imagined as a distance at which electromagnetic attraction is stopped by gravitational repulsion due to interior de Sitter vacuum.

In extended regular models based on nonlinear electrodynamics there exists a characteristic cutoff on self-energy whose value depends on a chosen density profile ([33] and references

therein). In regular models with de Sitter interior it can be qualitatively evaluated as

$$\frac{e^2}{r_e^4} \simeq 8\pi G\rho_0 = \frac{3}{r_0^2} \quad (22)$$

It gives a rough estimate for the characteristic length scale  $r_e$  at which electromagnetic attraction is balanced by de Sitter gravitational repulsion  $r_e = 1.05 \times 10^{-17} cm$  which is quite close to experimental value  $l_e$ , although estimate is qualitative and model-independent.

## 5 Summary

Nonlinear electrodynamics coupled to gravity predicts that spinning particles dominated by the electromagnetic interaction, would have to have de Sitter interiors arising naturally in the regular geometry asymptotically Kerr-Newman for a distant observer. De Sitter vacuum supplies a particle with the finite positive electromagnetic mass related to breaking of space-time symmetry [32].

In all asymptotically Kerr-Newman models, symmetry of an oblate ellipsoid (3) leads to estimates of the intrinsic radius of an internal disk by the Compton wavelength  $\simeq 3.9 \times 10^{-11} cm$ , and of the transverse size (thickness of ellipsoid) by the classical electron radius  $\simeq 2.8 \times 10^{-13} cm$ .

NED theories appear as low-energy effective limits in certain models of string/M-theories (for review [60, 61]). The above results apply to the cases when the relevant electromagnetic scale is much less than the Planck scale.

Experiments reveal the existence of a minimal length scale in the process of annihilation,  $l_e \simeq 1.57 \times 10^{-17} cm$  for the electron. This characteristic length can be explained as a distance at which electromagnetic attraction in annihilation is stopped by gravitational repulsion due to an interior de Sitter vacuum.

One can conclude that experiments suggest an extended electron picture.

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